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AFOSR Grant No. F49620-97-1-0050 (Evolving Expression-Linkage GA) has come to a close and this report details project accomplishment. Particularly notable was the invention of a new competent GA, the Bayesian Optimization Algorithm (BOA) that works by budding and using a probabilistic model of the best solution points seen so far. BOA scales well and solves very hard problems quickly reliably and accurately. Another notable achievement was the completion of a Erick Cantu-Paz's magisterial PhD dissertation entitled Designing Efficient and Accurate Parallel Genetic Algorithms." This thesis provides the first scaling laws that show why GAs are so easy to make parallel and how to do it better. These findings and accomplishments are discussed in the final project report together with others, including the development of a new theory of hybrid optimization and a. new theory of effective lime utilization. The report also details the affiliation and support of 26 researchers with the project, the publication, acceptance, or submission of 65 publications acknowledging AFOSR support, and numerous interactions and transitions.

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Final Report

The Design, Implementation Application, and Dissemination of an Evolving Expression-Linkage Genetic Algorithm

AFOSR Grant No. F49620-97-1-0050

15 February 1997 to 30 November 1999

David E. Goldberg
Department of General Engineering

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Final Report for
The Design, Implementation, Application, and Dissemination of an Evolving Expression-Linkage Genetic Algorithms AFOSR Grant No. F49620-97-1-0050

15 February 1997 to 30 November 1999

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Abstract

AFOSR Grant No. F49620-97-1-0050 (Evolving Expression-Linkage GA) has come to a close and this report details project accomplishment. Particularly notable was the invention of a new competent GA, the Bayesian Optimization Algorithm (BOA) that works by building and using a probabilistic model of the best solution points seen so far. BOA scales well and solves very hard problems quickly, reliably and accurately. Another notable achievement was the completion of a Erick Cantú-Paz's magisterial PhD dissertation entitled "Designing Efficient and Accurate Parallel Genetic Algorithms." This thesis provides the first scaling laws that show why GAs are so easy to make parallel and how to do it better. These findings and accomplishments are discussed in the final project report together with others, including the development of a new theory of hybrid optimization and a new theory of effective time utilization. The report also details the the affiliation and support of 26 researchers with the project, the publication, acceptance, or submission of 65 publications acknowledging AFOSR support, and numerous interactions and transitions.

1 Objectives

The augmented objectives (see previous project reports) of Grant No. F49620-97-1-0050 (Evolving Expression-Linkage GA) were as follows:

- Design and implement an evolving expression-linkage genetic algorithm (eelGA).
- Apply the eelGA to a problem of Air Force interest.
- Transfer this technology to Air Force personnel and vendors.
- Improve the efficiency of GAs by four means:
    1. parallelization techniques.

2. time utilization methods.
3. evaluation relaxation.
4. effective hybridization.

Significant progress was made in accomplishing each of these objectives, and this progress is briefly reviewed in the next section.

2 Status of Effort

The project has moved ahead with progress in each of the objective areas:

- Development of effective competent GAs.
- Development of effective efficiency techniques.
- Dissemination of the results to Air Force personnel and tackling problems of importance to the Air Force.

Each of these areas is briefly reviewed in what follows.

2.1 Competent GAs

The major task of the project was to advance the cause of *competent* genetic algorithms—GAs that solve hard problems, quickly, reliably, and accurately. Progress in this area over the course of the project has been substantial and included work on

1. The Bayesian optimization algorithm (BOA)
2. The linkage identification through non-linearity checking and monotonicity detection algorithms (LINC/LIMD)
3. The development of OmeGA, the ordering messy genetic algorithm

Martin Pelikan's (AFOSR-sponsored) work on the *Bayesian Optimization Algorithm* (BOA) is perhaps the most notable achievement of the project (and the subject of a follow-on project). Simply stated, the code builds a Bayes net model of the best points, using this model in place of crossover, mutation, and other genetic operators to speculate on the best points in the search space. Because of the generality of the Bayes net assumption, BOA can quickly search for optimal solutions under more general conditions than can a linkage-oriented solver. This is quite exciting, and the continuation of this work was proposed and funded by AFOSR and is currently ongoing.

Professor Masaharu Munetomo, a visitor from Hokkaido University in Japan, and the PI developed two new techniques for linkage identification and exploitation, the so-called LIMD and LINC GAs (Linkage identification through monotonicity detection and nonlinearity checking). These results may be viewed as alternatives to Kargupta's gene expression messy GA that also derived from IlliGAL activities sponsored by AFOSR.

Dimitri Knjazew, a visiting scholar from Dortmund, Germany, and the PI developed OmeGA, the ordering messy genetic algorithm for solving hard problems over permutations. Using previously supported fast messy GA technology, the researchers have come up with a way to solve difficult scheduling and sequencing problems quickly, reliably, and accurately.

2.2 GA efficiency enhancement

Progress in the area of GA efficiency is important, because even competent GAs should be expected to require significant computational resources. This project has pursued four types of speedups:

1. parallelization
2. time utilization
3. evaluation relaxation,
4. hybridization

Our first foray into the realm of efficiency enhancement came with Miller's groundbreaking thesis on optimal objective function sampling in the presence of noise. Miller's work used practical theory and careful experiment to demonstrate that GAs tend to prefer quick and noisy/dirty evaluation to slow and accurate in the solution of problems in a given time. Scaling laws were derived for the optimal sample sizing, and these were confirmed in practice. Follow-on work is now extending this results to function surrogates, optimal finite-elements and differential equation grid sizing, and other types of error-computation-time tradeoffs.

Among the most important accomplishments in this area was the recent completion of Erick Cantú-Paz's magisterial PhD dissertation *Designing Efficient and Accurate Parallel Genetic Algorithms* (UIUC, Computer Science, 1999). Parallel GAs have long been used in practice, but this usage has been largely without benefit of even the most rudimentary scaling laws. In one fell swoop, Cantú-Paz rectifies the situation with both bounding and exact models of parallel GA performance and design.

An important first model of global-local hybrids (Goldberg & Voessner, 1999) was developed to try to identify the optimal division between global searchers (like GAs) on the one hand and local searchers (those of OR and traditional optimization) on the other.

First theory on optimal time utilization (Goldberg, 1999) was derived as part of this project, and experimental work and theoretical refinement are continuing to try to ere performed this past year as a result of AFOSR funding

2.3 Dissemination of results to the AF and tackling AF-related projects

Dissemination of these results to the Air Force (and others) has been improved by placing greater emphasis on getting pilot codes up sooner. Pelikan's BOA, Harik's extended compact GA, and a version of Wilson's XCS have been made available (IlliGAL Technical Report Nos. 99011, 99016, and 99021). Additionally, at a program review meeting at WPAFB, I proposed a Workshop on Military Applications of Genetic and Evolutionary Computation at which it might be possible to give a tutorial on competent GAs and their application. Additionally, a meeting was held at WPAFB on July 8, 1999 to investigate the application of the methods of this proposal and the next to molecular conformation problems with Dr. Ruth Pachter of WPAFB.

Problems of military and Air Force interest have been pursued with other researchers throughout the course of this investigation, including antenna/absorber design, course-of-action selection in combat situations, design of molecules, scheduling applications, to name a few. Additional details are given under findings and transitions.

Taken together these results represent success across the spectrum of goals originally anticipated in the project. Specific accomplishments and findings are summarized in the next section.

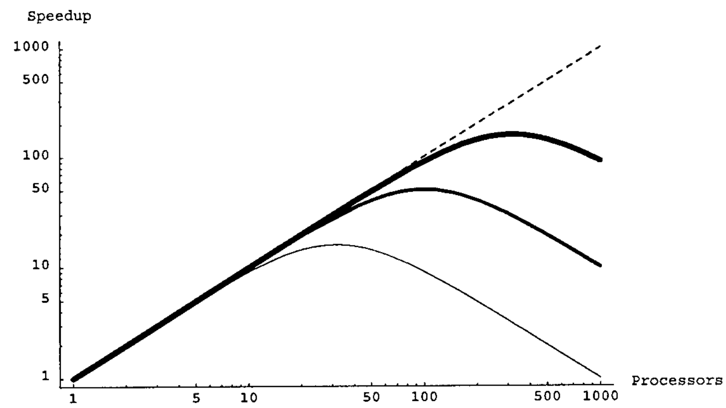

Figure 1: The speedup curve for master-slave parallelism is shown for three values of evaluation-communication time ratio $\gamma = 1, 10, 100$ from Cantú-Paz (1999).

3 Accomplishments and New Findings

This section highlights the key accomplishments and findings of the project.

BOA developed and published. Martin Pelikan has invented the Bayesian Optimization Algorithm (BOA), which builds and exploits a probabilistic model (a Bayesian network) of the population of best points seen by the algorithm. Because the Bayesian network is such a general representation, BOA has been found to solve a broad class of difficult problems, quickly, reliably, and accurately. First generation BOA code is available for Air Force use on the IlliGAL web site (http://www-illigal.ge.uiuc.edu), and work is continuing to improve BOA to handle hierarchical problems and alternative codings.

Parallel GAs unlocked. Erick Cantú-Paz has completed an important dissertation on the analysis and optimization of parallel genetic algorithms. Because of this work, we can now predict and optimize solution quality under differing topologies, migration rate, and population size. The work has exceeded our initial expectations and should be viewed as a turning point in the science and art of parallel GAs. For example, his bounding calculation for the number of processors required in master-slave parallelization

$$S' = \sqrt{\frac{\beta}{T_c} n}$$

where S'= the number of processors, β is the function evaluation time per individual, and T_c is the communication time per individual, shows us that large numbers of processors can be used effectively whenever function evaluation time greatly exceeds communications time—a situation that occurs in most problems of practical interest. The optimal result can be seen as the maximum in the speedup curve of figure 1. The speedup is approximately linear until a critical value of processor count of

$$S_c = \left(\frac{\beta}{T_c} n\right)^{1/3}$$

This is good news and suggests that many practical applications can expect near-linear speedups as additional processors are added to the task, even if the form of parallelization is no more sophisticated than a simple master-slave configuration.

DOI Book completed. The PI has completed a book entitled *The Design of Innovation: Lessons from Genetic Algorithms* and is now distributing chapters for review by others. The book brings together (1) the methodology, (2) the design theory, and (3) the competent GA designs that have been developed largely with AFOSR support. The book starts with a discussion of the Wright brothers' analogy the PI has used over the used to discuss GA design and continues with sections on little models and patchquilt integration using dimensional analysis. Chapters on building blocks, the schema theorem, selection timing, mixing, problem difficulty, and decision making bring IlliGAL design theory to a technical audience. Chapters on competent GAs (like the fmGA, LLGA, BOA, LINC-GA and so on) and the connection of competent GA design to human innovation cap off the volume. The book should be published in the year 2000.

LINC/LIMD GA, a new competent GA, designed. Professor Munetomo, a visitor from Japan, has invented two competent GAs: one called the LINC-GA (linkage identification by nonlinearity checking GA) and another called LIMD-GA (linkage identification by monotonicity detection). Both techniques are motivated by the idea of the detection of linkage groups through pairwise comparisons of alleles. Such a criterion is not adequate to detect the types of problems we are interested in (not all nonlinear problems are hard). Nonetheless, Dr. Munetomo has devised methods to rectify this difficulty. The method gives us one more tool in the arsenal of competent GA design, and it also is helpful in understanding similarities and differences between the various methods that have been established to date.

Economics of hybridization model developed. The PI performed first analyses and experiments (with Dr. Siegfried Voessner, Engineering Economics and Operations Research, Stanford University) on a theory of hybridization economics. Most GAs in practice are hybrids between genetic algorithms and some local search technique, and such combinations have been quite successful at achieving good answers quickly, but there has been less inquiry into how to divide one's effort between the different schemes, and in our work we have constructed a first theory of economic combination that suggests how to divide ones time between local and global search using minimal assumptions about the search space and the searchers. Figure 2 shows the theoretical vs. experimental results for a random global searcher used alone versus one used with a local search technique. In the particular case, theory predicts that the global random search should be superior to G+L as is measured in practice.

Time utilization analysis performed. Effective time utilization is demonstrated to be the missing link between crossover and mutation in a study sponsored by this project. The article "Using time efficiently: Genetic-evolutionary algorithms and the continuation problem." (Goldberg, 1999), makes the point that salience distribution and signal-to-noise processing are the usual determinates of whether a building block is processed in parallel with others, or serially when SNR ratios are favorable. A bounding analysis suggests a dividing line between the two types of behavior that is quite dramatic.

BOA, XCS, and ECGA code made available. Pelikan's Bayesian Optimization Algorithm (BOA), Butz's version of Wilson's XCS code, and Harik's Extended Compact GA have been published as C++ code on the IlliGAL web site (http://www-illigal.ge.uiuc.edu).

fmGA study of scheduling problems with random keys. The random keys coding is used together with the AFOSR-supported fast messy GA (fmGA) to tackle difficult scheduling problems in the ordering messy genetic algorithm (OmeGA). Initial results are exciting and suggest that the combination of coding and fmGA work quickly, reliably, and accurately on target problems of considerable bounded difficulty. Recently completed results show that OmeGA scales to real scheduling problems.

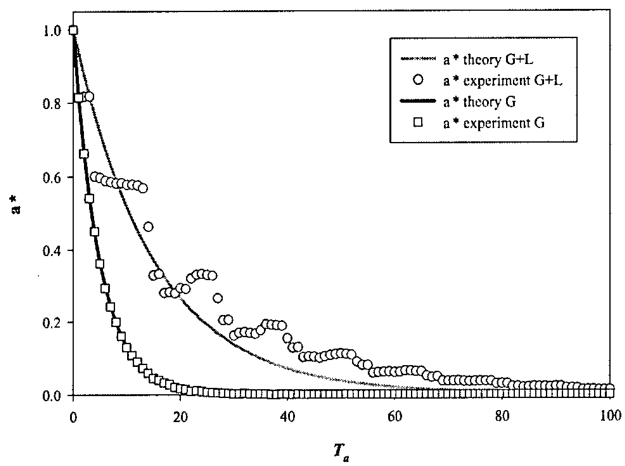

Figure 2: The probability of not achieving solution as a function of allowable number of function evaluations for a global scheme only or global+local hybrid matches the model of Goldberg & Voessner, 1999)

XCS coded and applied to engine test problem. As part of cooperative work with the National Center for Supercomputing Applications, Stewart Wilson's XCS genetics-based classifier system has being coded (by Martin Butz) and applied to an engine test problem for Caterpillar. It is fully operational and is now available for Air Force (and other personnel).

ACS investigation underway. Martin Butz is also continuing his work on Stolzmann's so-called *anticipatory classifier system* (ACS). The ACS learns new rules by minimizing the difference between what the system *anticipates* and what it *observes.* ACS has been used on small problems, and these efforts are to understand how to enable ACS-like techniques scale to real problems in classification.

Optimal sample size work continued. Phillipe Giguère has continued Brad Miller's important work on optimal sample sizing by looking at the case of *sampled fitness functions* in which sampling can result in the elimination of sampling error in a finite number of samples. In a sampled one-max problem, the small sample sizes suggested by the Miller bounds do not hold up, and the solution quality is surprisingly indifferent to variation of the number of samples. We were also surprised to observe the sensitivity of the analytical calculations to changes in the population sizing model. Additional work needs to be done, but this work shows that some care should be exercised in extrapolating the Miller work beyond its intended domain of application.

Population sizing shown to be proper bound. The PI has collaborated with Günter Rudolph at Dortmund University and have shown that the gambler's ruin population sizing model we now use is a proper bound of the full Markov chains. This result should help persuade the theory community of the soundness of our approach.

Facetwise analysis of genetic programming initiated. Working with Una-May O'Reilly at the MIT AI lab, the PI has initiated the process of carrying over the method of his AFOSR studies to genetic programming. This work is critical, because (1) GP is the fastest growing segment of the field, and (2) GP related methods hold the greatest promise to solve deep, difficult problems in many fields. The first two papers resulting from this collaboration have been published. The first discusses different types of *expression* mechanisms and their relationship to where program material resides in a genetic program. The second discusses the relationship between building block salience and temporal sequence of processing. Understanding these two items sets the stage for a better understanding of the critical issues of population sizing and mixing, work that is continuing.

Linkage learning code compressed and made available. Harik's linkage learning GA has been published in an efficient compressed form. This permits us to use introns or non-coding segments of arbitrary length without arbitrarily large memory requirements. It also makes the code available for the first time to Air Force and other users.

4 Personnel Supported

This section details the individuals supported on these projects.

4.1 Faculty supported

Professor David E. Goldberg, the principal investigator, was supported on eelGA during the summer 1999.

4.2 Faculty affiliated with the project

The following is a list of visiting faculty working on topics related to the project whose primary support comes from another source. Nonetheless, their supervision by Professor Goldberg was supported by AFOSR funds, and some travel or incidental expenses may have come from AFOSR monies.

1. Professor Masaharu Munetomo (Hokkaido University)
2. Professor Yuji Sakamoto (Muroran Institute of Technology)
3. Professor Dirk Thierens (University of Utrecht)

4.3 Graduate students supported

The following is a list of graduate students supported. Unless otherwise indicated all students are or were affiliated with the University of Illinois.

1. M. Pelikan (UIUC PhD CS)
2. D. Knjazew (Dortmund University)
3. L. Wang (UIUC, MS, ECE)

4.4 Graduate students affiliated with project

The following is a list of students working on topics related to the project whose primary support comes from another source. Nonetheless, their supervision by Professor Goldberg was supported by AFOSR funds, and some travel or incidental expenses may have come from AFOSR monies.

1. M. Butz (University of Wuerzburg, Germany)
2. E. Cantú-Paz (UIUC, Supported by Fulbright)
3. P. Giguère (UIUC)
4. G. Harik (Michigan)
5. J. Horn (UIUC)
6. F. Lobo (Nova University, Lisbon)
7. O. Mengshoel (UIUC)
8. B. Miller (UIUC)
9. A. Pereira (Nova University, Lisbon)

4.5 Undergraduate students supported

The following is a list of undergraduate research assistants who have been supported by AFOSR funds:

1. J. Borgerson
2. B. Dunn
3. R. Gadient
4. P. Gallego
5. K. Garner
6. A. Herzog
7. M. Magin
8. B. Sutton
9. B. Wagus
10. K. Zacarias

5 Publications

Publications submitted, accepted, and published over the course of the project are presented in this section.

5.1 Submitted

Butz, M. V., Goldberg, D. E., & Stolzmann, W. (2000). Probabililty-enhanced predictions in the anticipatory classifier system. *Proceedings of the 2000 International Workshop on Learning Classifier Systems.*

Butz, M. V., Goldberg, D. E., & Stolzmann, W. (2000). Investigating generalization in the anticipatory classifier system. *Parallel Problem Solving from Nature.*

Knjazew, D., & Goldberg, D. E. (2000). Large-scale permutation optimization with the ordering messy genetic algorithm. *Parallel Problem Solving from Nature.*

Pelikan, M., & Goldberg, D. E. (2000). Genetic algorithms, clustering, and the breaking of symmetry. *Parallel Problem Solving from Nature.*

Pelikan, M., & Goldberg, D. E. (2000). Research on the Bayesian optimization algorithm. *Parallel Problem Solving from Nature.*

Reed, P., Minsker, B., & Goldberg, D. E. (2000). Designing a competent simple genetic algorithm for search and optimization. *Water Resources Research.*

Rothlauf, F., & Goldberg, D. E. (2000). Pruefernumbers and genetic algorithms: A lesson how the low locality of an encoding can harm the performance of GAs. *Proceedings of EuroTel 2000.*

Stolzmann, W., Butz, M. V., Hoffman, J., & Goldberg, D. E. (2000). First cognitive capabilities in the anticipatory classifier system. *Proceedings of the 2000 International Conference on the Simulation of Adaptive Behavior.*

5.2 Accepted but not published

Butz, M. V., Goldberg, D. E., & Stolzmann, W. (in press). Introducing a genetic generalization pressure to the anticipatory classifier system, Part I: Theoretical approach. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Butz, M. V., Goldberg, D. E., & Stolzmann, W. (in press). Introducing a genetic generalization pressure to the anticipatory classifier system, Part 2: Performance analysis. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Cantú-Paz, E. (in press). Implementing fast and reliable parallel genetic algorithms. In Chalmers, L. (Ed.) *Handbook of practical genetic algorithms, III*, Boca Raton, FL: CRC Press.

Cantú-Paz, E., & Goldberg, D. E. (in press). Efficient parallel genetic algorithms: Theory and practice. *Computational Methods in Applied Mechanics and Engineering.*

Goldberg, D. E. (in press). The design of innovation: Lessons from genetic algorithms, lessons for the real world. *Technological Forecasting & Social Change.*

Goldberg, D. E. (in press). Genetic and evolutionary algorithms in the real world. *Information Processing Society of Japan Magazine* [In Japanese, N. Adachi, trans.]. (also IlliGAL 99013 in English)

Goldberg, D. E., & Deb, K. (in press). Genetic and evolutionary computation in computational mechanics and engineering: Preface to a special edition. *Computational Methods in Applied Mechanics and Engineering.*

Harik, G., & Goldberg, D. E. (in press). Linkage learning through probabilistic expression. *Computational Methods in Applied Mechanics and Engineering.*

Knjazew, D. & Goldberg, D. E. (in press). OMEGA—Ordering Messy GA: Solving permutation problems with the fast lmessy genetic algorithm and random keys. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Munetomo, M. & Goldberg, D. E. (in press). Linkage identification by non-monotonicity detection for overlapping functions *Evolutionary Computation.*

Osyzcka, A., Tamura, H., & Goldberg, D. E. (in press). A bicriterion approach to constrained optimization problems using genetic algorithms. *Evolutionary Optimization Journal.*

Pelikan, M. & Goldberg, D. E. (in press). Hierarchical problem solving by the Bayesian optimization algorithm. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Pelikan, M., Goldberg, D. E., & Cantú-Paz, E. (in press). Bayesian optimization algorithm, population sizing, and time to convergence. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Pelikan, M., Goldberg, D. E., & Cantú-Paz, E. (in press). BOA: The Bayesian Optimization Algorithm. *Evolutionary Computation.*

Pelikan, M., Goldberg, D. E., & Lobo, F. (in press). A Survey of optimization by building and using probabilistic models. *Computational Optimization and Applications.*

Pelikan, M., Goldberg, D. E., & Lobo, F. (in press). A survey of optimization by building and using probabilistic models. *Proceedings of the 2000 American Controls Conference.*

Pelikan, M. & Lobo, F. (in press). Parameter-less genetic algorithm: A worst-case time and space complexity analysis. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Rothlauf, F. & Goldberg, D. E. (in press). Pruefernumbers and genetic algorithms: A lesson how the locality of an encoding can harm the performance of GAs. *Proceedings of EuroTel 2000.*

Rothlauf, F., Goldberg, D. E., & Heinzl, A. (in press). Bad codings and the utility of well-designed genetic algorithms. *GECCO-2000 Proceedings of the Genetic and Evolutionary Computation Conference.*

Weile, D. S., Michielssen, E., & Goldberg, D. E. (in press). The compact genetic algorithm: A litmus test for genetic algorithm applicability. *Proceedings of the IEEE Workshop on Electromagnetic Systems.*

5.3 Published

Cantu-Páz, E, & Goldberg, D. E. (1997). Predicting speedups of ideal bounding cases of parallel genetic algorithms. *Proceedings of the Seventh International Conference on Genetic Algorithms,* 113–120.

Cantu-Páz, E, & Goldberg, D. E. (1997). Modeling idealized bounding cases of parallel genetic algorithms. *Genetic Programming 1997: Proceedings of the Second Annual Conference,* 353–361.

Cantú-Paz, E. (1998). Designing efficient master-slave parallel genetic algorithms. *Genetic Programming 1998: Proceedings of the Third Annual Conference,* 455.

Cantú-Paz, E. (1998). A survey of parallel genetic algorithms. *Calculateurs Paralleles, Reseaux et Systems Repartis, 10*(2), 141-171.

Cantú-Paz, E. (1998). Using Markov chains to analyze a bounding case of parallel genetic algorithms. *Genetic Programming 1998: Proceedings of the Third Annual Conference,* 456–462.

Cantú-Paz, E. (1999). Migration policies and takeover times in genetic algorithms. *GECCO-99 Proceedings of the Genetic and Evolutionary Computation Conference*, 775.

Cantú-Paz, E. (1999). Topologies, migration rates, and multi-population parallel genetic algorithms, *GECCO-99 Proceedings of the Genetic and Evolutionary Computation Conference*, 91–98.

Cantú-Paz, E., & Goldberg, D. E. (1999). On the scalability of parallel genetic algorithms. *Evolutionary Computation, 7* (4), 429–449.

Giguère, P., & Goldberg, D. E. (1998). Population sizing for optimum sampling with genetic algorithms: A case study of the onemax problem. *Genetic Programming 1998: Proceedings of the Fourth Annual Conference,* 496–503.

Goldberg, D. E. (1999). From genetic and evolutionary optimization to the design of conceptual machines. *Evolutionary Optimization Journal, 1*(1), 1–12.

Goldberg, D. E. (1999). A meditation on the application of genetic algorithms. In Y. Rahmat-Samii & E. Michielssen, *Electromagnetic optimization by genetic algorithms* (pp. xxi–xxvi).

Goldberg, D. E. (1999). The race, the hurdle, and the sweet spot: Lessons from genetic algorithms for the automation of innovation and creativity. In P. Bentley, *Evolutionary design by computers.* San Francisco: Morgan Kaufmann (pp. 105–118).

Goldberg, D. E. (1999). Using time efficiently: Genetic-evolutionary algorithms and the continuation problem. *GECCO-99 Proceedings of the Genetic and Evolutionary Computation Conference*, 212–219.

Goldberg, D. E., & O'Reilly, U. (1998). Where does the good stuff go, and why? How contextual semantics influence program structure in simple genetic programming. *Proceedings of the First European Workshop on Genetic Programming.*

Goldberg, D. E., & Wang, L. (1998). Adaptive niching via coevolutionary sharing. In D. Quagliarella, J. Périaux, C. Poloni, and G. Winter (Eds.) *Genetic algorithms and evolution strategies in engineering and computer science* (pp. 21–38). Chichester: Wiley.

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Koza, J. R., Banzhaf, W., Chellapilla, K., Deb, K., Dorigo, M., Fogel, D. B., Garzon, M. H., Goldberg, D. E., Iba, H., & Riolo, R. L. (Eds.) (1998). *Genetic Programming 1998: Proceedings of the Third Annual Conference.*

Lobo, F. G., Deb, K., Goldberg, D. E., Harik, G., & Wang, L. (1998). Compressed introns in a linkage learning genetic algorithm. *Genetic Programming 1998: Proceedings of the Third Annual Conference,* 551–558.

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6 Interactions and Transitions

This section lists meeting participation, presentations, and transitions.

6.1 Meeting participation and presentation, 1998–1999

During project year 1998–1999 Professor Goldberg gave invited lectures as follows:

Chevron Lecture Series. A six-hour series of lectures entitled *Simplifying complexity: Competent genetic algorithms as a model of and mechanism for innovating in complex systems* was given in the Bay area and distributed through the company on videotape.

Templeton Seminar. Participated in the Templeton workshop on *Accelerating Creativity*, and gave the lecture "The Design of Innovation: Lessons from Genetic and Evolutionary Computation."

IIT Madras. Was invited to India and gave a series of four lectures at IIT Madras with attendance from governmental agencies and corporate representatives in addition to campus attendance.

HollandFest. Was invited to make a presentation at a Festschift honoring John Holland's 70th birthday and gave the presentation "An Integrated, Effective Theory of Building Block Difficulty."

GECCO 99. Chaired GECCO 99 and gave two talks, one on "Optimizing global-local search hybrids" and another on "Using time efficiently: Genetic-evolutionary algorithms and the continuation problem."

IWSCI 99. Shared stage with Lofti Zadeh at International Workshop on Soft Computing in Industry in Japan and gave the talk "The Race, the Hurdle, and the Sweet Spot: Genetic Algorithms as a Computational Model of Innovation."

EP99. Participated in Electronic Prototyping 99 at WPAFB, giving the talk "Competence and Efficiency in Genetic Algorithm Design: What it Means to Real Users."

Expert Systems 98. Gave the keynote address at Expert Systems 1998 at Cambridge University and gave the talk, "The Race, the Hurdle, and the Sweet Spot: Three Lessons from Genetic Algorithm Design for the Understanding of Human Innovation.

Professor Goldberg's affiliates and students were active presenters and participants during project year 1998–1999 as well:

1. E. Cantu-Páz presented "Using Markov Chains to analyze a bounding case of parallel genetic algorithms" and Designing efficient master-slave parallel genetic algorithms (a poster) at GP 98 in Madison, Wisconsin.

2. Phillipe Giguère presented "Population sizing for optimum sampling with genetic algorithms at GP 98, Madison, WI.

3. Fernando Lobo presented "Compressed introns in a linkage learning genetic algorithm" at GP 98, Madison, WI.

4. Ole Mengshoel presented "Deceptive and other functions of unitation as Bayesian networks" at GP 98, Madison, WI.

5. E. Cantu-Páz presented " Migration policies and takeover times in genetic algorithms" as a poster, "Topologies, migration rates, and multi-population parallel genetic algorithms" as a full paper, and he also chaired a workshop on Parallel GAs and gave an invited tutorial on parallel GAs at GECCO-99 in Orlando, FL.

6. Fernando Lobo presented " A parameter-less genetic algorithm" at GECCO-99 as a full paper.

7. Masaharu Munetomo presented "A genetic algorithm using linkage identification with monotonicity detection" at the 1999 IEEE Conference on Systems, Man, & Cybernetics in Japan, and "Identifying linkage groups by nonlinearity/non-monotonicity detection" at GECCO-99.

8. Martin Pelikan presented "BOA: The Bayesian Optimization Algorithm" at GECCO-99 as a full paper.

6.2 Meeting participation and presentation, 1997–1998

During the project year 1997–98, Professor Goldberg gave invited seminars at Dortmund University, GMD (Bonn), Daimler Benz (Berlin). Technical University of Berlin, Leiden University, Utrecht University, the University of Central England (Birmingham). UCLA (Los Angeles). USC (Los Angeles), UCSD (La Jolla, California), Stanford University, University of Paris VI, Dassault Aviation (Paris), and . Additionally he gave invited tutorial lectures at Eurogen 98 in Trieste, Italy, Hydroinformatics 98 in Copenhagen, Denmark, and Genetic Programming 98 in Madison, Wisconsin.

Professor Goldberg also gave a keynote lecture at Hydroinformatics 98 in Copenhagen and invited lectures at Navigating Complexity (Portland, Oregon) and EUROGEN 98 (Trieste, Italy).

Professor Goldberg's affiliates and students were active presenters and participants as well:

1. E. Cantu-Páz presented "Using Markov Chains to analyze a bounding case of parallel genetic algorithms" and Designing efficient master-slave parallel genetic algorithms (a poster) at GP 98 in Madison, Wisconsin.

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3. Fernando Lobo presented "Compressed introns in a linkage learning genetic algorithm" at GP 98, Madison, WI.

4. Ole Mengshoel presented "Deceptive and other functions of unitation as Bayesian networks" at GP 98, Madison, WI.

6.3 Meeting participation and presentation, 1997

During the first project year, Professor Goldberg gave invited lectures at Osaka Institute of Technology, Osaka Kyoiku University, Hitachi Corporation, the Tokyo Institute of Technology, the Japan Society of Mechanical Engineers Meeting, the IMA Workshop on Evolutionary Computation (U. Minnesota), Los Alamos National Laboratory, the Rowland Institute for Science, and the MIT AI Laboratory. He also presented "Modeling idealized bounding cases of parallel genetic algorithms." at GP 97.

Professor Goldberg's affiliates and students were active presenters and participants as well:

1. E. Cantu-Páz presented "Predicting speedups of ideal bounding cases of parallel genetic algorithms" at ICGA 97 in East Lansing, Michigan.
2. G. Harik presented "Learning Linkage" at FOGA IV in San Diego and "The gambler's ruin problem, genetic algorithms, and the sizing of populations" at ICEC 97 in Indianapolis.
3. J. Horn presented "Genetic algorithms (with sharing) in search, optimization, and machine learning" at FOGA IV in San Diego.
4. F. Lobo presented "Decision making in a hybrid genetic algorithm" at ICEC 97 in Indianapolis.
5. Y. Sakamoto presented "Takeover time in noisy environments" at ICGA 97.

6.4 Transitions

EvoNews Article. The PI's research and views on the field were highlighted in an article in the influential newsletter of the European EvoNet, a network of European researchers on genetic algorithms.

CMAME Journal. The PI edited a special edition of the influential journal Computational Methods in Applied Mechanics and Engineering devoted to genetic and evolutionary computation. The issue contains 19 articles on theory, implementation, and application with the lion's share being applications to engineering.

GECCO-99. The PI chaired the 1999 Genetic and Evolutionary Computation Conference held in Orlando, Florida from July 13-17, 1999. 619 people attended the conference with 15 workshops, 25 tutorials, a 1000-page proceedings. Next year's conference will be held in Las Vegas (www.genetic-algorithm.org).

GA course online. PI's GA course (GE 485) is now being offered online via the web this semester. 8 off-campus and 25 on-campus students are taking the course, and we expect the off-campus attendance to scale up following the pilot semester. Credit can be obtained through UIUC or the National Technological University (NTU).

Application with Caterpillar. Following a short course given to 25 engineers at Caterpillar in Peoria by the PI, PI contracted to apply GAs to a cooling system design problem.

Telecommunications problems. A visitor from German, Franz Rothlauf (University of Bayreuth) and the PI worked on solving some telecommunications problems using random keys codings.

GA-based companies. There are growing numbers of GA-based companies in the US and around the world using technology affected by my work. Optimax, a GA-based scheduling software firm has an integrated product for factory scheduling; Optimax recently sold out for close to $60M to I2, another scheduling software firm. The Schema Company in Israel has a GA-based software product named Orca for scheduling container ships that is used by a substantial fraction of the container fleet. Silicon Biology in Minnesota has developed a data-entry software package with GA-based technology at its core. Many large and small financial services firms are using GAs to make portfolio and trading decisions.

Increase in on-campus applications. PI participated in a larger number of applications PhD theses in applications areas, including traffic control, spacecraft trajectory optimization, electromagetic design, environmental plume detection, molecular design to name a few.

Real biology. Using GA-like techniques, Jay Mittenthal and PI will examine some basic questions in evolutionary biology with algorithms that resemble messy GAs.

Pipe network optimization. A center in England has spawned a company called Optimal Solutions that uses structured messy genetic algorithms to optimize water pipelines. Of course, mGAs trace their lineage through AFOSR-sponsored work.

Battlefield courses of action. A student project in PI's GA course in 1997 turned into a major focus of Army work in the generation and analysis of battlefield courses of action. I have joined the Army Federated Laboratory project centered at Illinois to work on GA improvements of the growing Fox system pioneered by Stu Schlabach.

Working group on genetic and evolutionary computation. The PI has started the Illinois Working Group on Genetic and Evolutionary Computation (IWGGEC) at UIUC to try to gain leverage on the growing work at Illinois in this field. At present, there are over 26 faculty with some involvement in the field. The hope is that intellectual and joint funding initiatives can build ideas and realize synergy and economy among Illinois efforts.

Electromagnetic applications. PI continued to work with E. Michielssen and Dan Weile here at the University of Illinois on applying multiobjective GAs to the solution of antenna and absorber design. Professor Michielssen is under contract to AFOSR with a project "Electromagnetic Scattering from Complex Structures." Recent studies have concentrated on carrying over the compact GA and extended compact GA of Harik to real electromagnetics problems.

US News Article. The PI's research and views on the field were highlighted in an article on genetic and evolutionary computation in US News and World Reports (July 27, 1998). The article highlighted the transition that is now taking place from the laboratory to the real world.

Technology transfer in financial applications. Ole Mengshoel, a project-affiliated UIUC graduate student worked as an intern for First Quadrant, a company that manages large portfolios of stocks for institutional clients using genetic algorithms. Lab technology was transfered to a working system and more such interaction is planned.

Technology transfer in hydroinformatics. The PI's keynote address at Hydroinformatics 98 led to a number of invitations to consult with software firms in hydraulic and hydrologic applications. A private short course was held to transfer the latest GA techniques to a company in California.

Pipe network optimization. A center in England has spawned a company called Optimal Solutions that uses structured messy genetic algorithms to optimize water pipelines. Of course, mGAs trace their lineage through AFOSR-sponsored work.

Machine tool fault detection. Two students in my GA class working with UIUC faculty Dick DeVor developed and published a machine-tool fault detection system that uses a GA to determine whether parameters from a drill bit are out of range and should be flagged as a fault. This work has led to a PhD-level investigation of GA usage in this problem area.

Self-assembling molecules. A material science student Milan Keser finished a PhD under the direction of noted material scientist Sam Stupp to predict the conformation of certain self-assembling molecules. Results are were excellent and have been published in prominent scientific journals.

7 New discoveries, inventions, or patent disclosures

Although much of the work under this project could be classified as new discoveries or inventions, no patent applications, filings, or other attempts to register intellectual property were made this past year.

8 Honors and Awards

This section lists awards for the PI and his students.

8.1 PI honors and awards

Professor Goldberg was on sabbatical for the academic year 1997-98 during which he continued his AFOSR work. He was named a Gambrinus Fellow at the University of Dortmund for the fall semester 1997 and was named a visiting scholar at Stanford Medical Informatics.

Professor Goldberg received the 1996 ASEE Wickenden Award for best paper in the *Journal of Engineering Education* for his paper entitled "Change in Engineering Education: One Myth, Two Scenarios, and Three Foci."

Professor Goldberg was named an Associate of the Center for Advanced Study (CAS) at the University of Illinois for the fall semester 1995 and was released of teaching duties for that semester. During the CAS semester, he worked on AFOSR projects and wrote a portion of a manuscript entitled *The Design of Innovating Machines: Lessons from Genetic Algorithms.*

Professor Goldberg was named an NSF Presidential Young Investigator in 1985.

8.2 Student honors and awards

Erick Cantù-Paz received a renewal award for his Fulbright Fellowship.